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THE AERODYNAMIC INFLUENCES OF ROTOR BLADE TAPER, TWIST, AIRFOIL--ETC(U)
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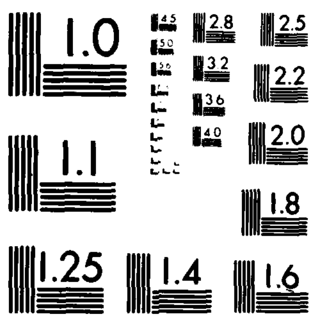
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THE AERODYNAMIC INFLUENCES OF ROTOR BLADE TAPER, TWIST, AIRFOILS AND SOLIDITY ON HOVER AND FORWARD FLIGHT PERFORMANCE

GENE J. BINGHAM, MR.
STRUCTURES LABORATORY
US ARMY RESEARCH & TECHNOLOGY LABORATORIES (AVRADCOM)
LANGLEY RESEARCH CENTER, HAMPTON, VA 23665

Introduction

The use of composites for helicopter rotors and the development of new airfoils has provided new opportunities in blade design. With composites, the fabrication of non-rectangular blades with variations in airfoil sections along the blade radius is practical. The advantages of non-rectangular rotor blades and variations in twist distribution and airfoils were considered in the late 1940's (refs. 1 to 5). These studies addressed rotors operating at relatively low tip speeds and forward flight velocities. For the configurations considered, increasing the twist from zero to -12 degrees provided thrust increases up to 4 percent and tapering the blades from root to tip increased the thrust an additional one or two percent in hovering flight. The analysis of the influences of twist and planform was not extended to forward flight.

Because current rotor tip speeds and flight speeds are significantly higher than those of references 1 to 5 and that rotor analyses techniques have been improved, a study has been performed to consider the influences of blade taper, point of taper initiation, twist, solidity, and airfoil on rotor efficiency in hover and forward flight. The study began with the design of an advanced rotor for the UH-1 helicopter. The initial design goal was to reduce hover power required by 8 ~~percent~~ % without degrading forward flight performance. This reduction was to be accomplished with an aircraft gross weight of 8050 pounds while operating at an altitude of 4000 feet and a temperature of 95°F.

The study indicated that the design goal could be exceeded. Based on this result, models of the baseline and advanced blade have been evaluated in the Langley V/STOL wind tunnel ~~(refs. 6 and 7)~~ and the analytical study has been extended to other helicopter configurations within the US Army inventory. This paper is to describe the design philosophy applied.

The influence of blade planform and twist on rotor performance are considered first for hover and then for forward flight. These influences initially are made independent of airfoil characteristics; after the influences of blade geometry are described, the airfoil requirements are addressed.

Discussion

Analytical Approach

The analytical results presented in this paper have been developed by using a simple hover and forward flight analyses. The programs were selected for high computer productivity and do provide qualitative results. The hover analysis combines the momentum theory and the blade-element theory (ref. 5). The forward flight analysis is tailored after references 8, 9, and 10; the rotor characteristics considered include thrust, profile-drag power, total power, flapping, rolling and pitching moments, direction of the resultant force vector, and the harmonic contributions of each rigid blade on the rotor to the shear-force input to the hub. Both the hover and forward flight analyses apply two-dimensional airfoil data tables in performing the blade element integrations. The Rotorcraft Flight Simulation Computer Program, C81 (ref. 11), was applied in the final forward flight analysis.

The initial steps in the analysis are to evaluate the influences of blade twist and taper on rotor performance and to identify the desired airfoil aerodynamic characteristics. The influence of airfoil stall and drag divergence are avoided in these steps by applying an "ideal" airfoil. The aerodynamic characteristics of this airfoil include a constant lift curve slope for all angles of attack and a constant drag coefficient (selected to be 0.0070) at all angles of attack and Mach numbers. The blade section lift coefficients of the blade-element computations will be equal to those of a "conventional" airfoil operating in the linear lift coefficient-angle of attack range.

Hover Analysis

The influences of blade taper ratio and the radial station at which taper begins is presented in figure 1. The ordinate is figure of merit $\left(\text{F.M.} = 0.707\, C_T^{3/2}/C_Q\right)$ and the abscissa indicates the radial station at which blade planform taper begins; the blades would be rectangular to the station where taper begins and the completely

rectangular blade would be represented at a value of 1.0. As previously noted, a UH-1 type rotor blade is considered; and for this figure the area solidity (σ = .0464) is constant.

The most significant change in figure of merit observed results from the change in radial station where taper is initiated. The increase is as great as 12 percent (F.M. = 0.80 compared to 0.715) by changing from a rectangular blade to a blade tapered from 0.2R. For each taper ratio, nearly one-half of the increases shown results from a blade which is rectangular to 0.90R and then tapered to the blade tip; moving the taper initiation inboard of 0.50R has little influence on figure of merit at some taper ratios. The influence of taper ratio tends to increase as the onset of taper is moved inboard. For example, at 0.50R increasing taper ratio from 3 to 9 results in a figure of merit increase of about 2.6 percent (F.M. - 0.775 to 0.795). The indicated favorable influences of location of taper initiation and taper ratio result from (1) the increased inboard loading of the rotor which decreases induced torque and (2) the reduction in chord in the outboard regions which decreases profile torque. The increased inboard loading decreases induced torque because the induced torque is a function of the product of airfoil section lift coefficient, chord, and radius squared; therefore, an advantage exists in distributing the greater lift coefficient and chord at the inboard radial stations. The reduction in chord in the outboard regions decreases the profile torque because the profile torque is a function of the product of airfoil section drag coefficient, chord, and radius squared; therefore, an advantage can be seen in reducing blade chord at the outboard radial stations.

As will be discussed later, maintaining a constant area solidity (as for fig. 1) may not be feasible in the final process of combining planform,

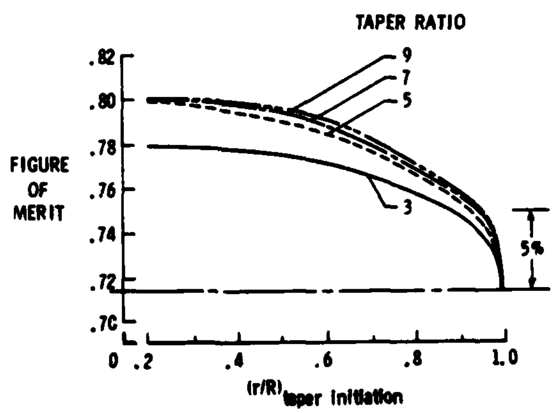


Figure 1.-Influence of location of initiation of taper and taper ratio on figure of merit, σ = 0.0464, θ = -10.6°, 8050 lbs, 4000'/95°.

twist, and airfoils due to airfoil section stall. Therefore, figure 2 is defined to consider the influence of a constant thrust weighted solidity. In providing improvements for existing rotor configurations, maintaining the thrust weighted solidity may not be necessary but should be the maximum solidity required. The trends are similar to those with constant area solidity but the differences in figure of merit due to position of taper initiation and taper ratio are reduced in magnitude. In this case, the increases in figure of merit are as great as 6 percent which is only one-half that indicated with a constant area solidity. An analysis of these results (where thrust is considered to be constant) reveals that for a given position of taper initiation and taper ratio the induced torque is unchanged by variations in solidity. The induced torque is unchanged since the radial distribution of lift for a given configuration is unchanged; at a given radial station, an increase in chord is inversely proportional to the decrease in lift coefficient, so the product of lift coefficient and local chord is unchanged. Therefore, the differences in figure of merit with changes in solidity are due entirely to differences in profile torque which result from differences in local airfoil chord. As will be shown in the discussion of the airfoil requirements section of this paper, the solidity applied depends on the combined influences of planform, twist, and the aerodynamic characteristics of the airfoil section selected.

The influence of changes in linear twist are presented in figure 3 for a taper ratio of 3. An increase in twist would, of course, result in a general increase in inboard loading and corresponding decrease in outboard loading to have an influence similar to that described for the previous figures; for a given planform, only the induced torque would be influenced for the "ideal" airfoil which has a constant drag coefficient. The most significant increase in figure of merit due to twist is indicated for the

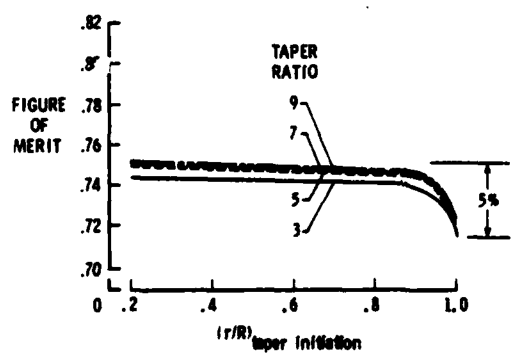


Figure 2.-Influence of location of initiation of taper and taper ratio on figure of merit, $\sigma_T = 0.0464$, $\theta = -10.6°$, 8050 lbs, 4000'/95°.

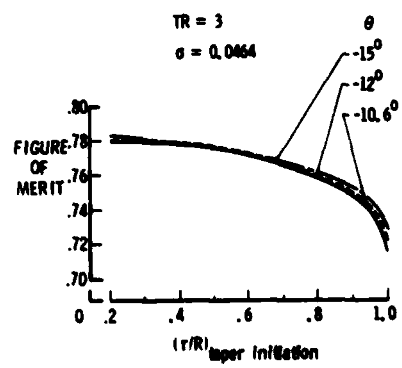


Figure 3.-Influence of linear twist on figure of merit, $\sigma = 0.0464$, 8050 lbs, 4000'/95°.

rectangular planform (r/R = 1.0); the increase in twist from -10.6° to -15° increases the figure of merit about 2 percent. As the taper initiation position is moved inboard, the influence of increased twist is reduced.

Forward Flight Analysis

The influence of blade taper and the radial station at which taper is initiated on forward flight performance is indicated in figure 4. The ordinate is torque coefficient and the abscissa again defines the radial position where taper is initiated. The forward flight velocity considered is 110 knots (near maximum for the UH-1 in level flight); the area solidity is constant, inflow is uniform, and the other parameters are the same as those for figure 1. Similar to the case for hover, a significant change in torque coefficient results from changes in radial station where taper is initiated; the decrease is as great as 16 percent by initiating taper at 0.2R. Unlike the previously discussed case for hover (fig. 1), only a small part of the total decrease results from changing the blade from fully rectangular to a configuration with taper initiated at 0.9R and the advantage of moving the taper initiation location inboard of 0.5R is greater in forward flight than in hover. As for the hover case, increases in taper ratio from 3 to 9 provide several percent decreases in torque coefficient. The favorable influences are due to the inboard loading and the reduction in chord in the outboard regions.

The results of the forward flight analysis with constant thrust weighted solidity are presented in figure 5. As for hover, the increased

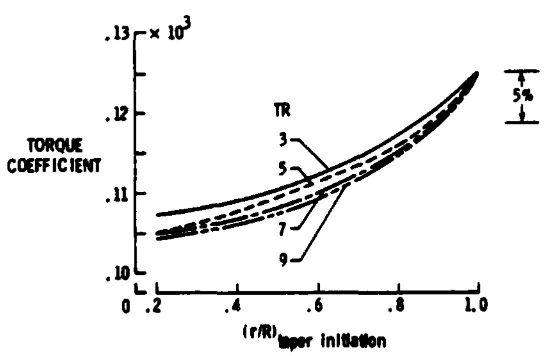


Figure 4.-Influence of location of initiation of taper and taper ratio on torque coefficient, σ = 0.0464, θ = -10.6°, 8050 lbs, 4000'/95°, 110 knots.

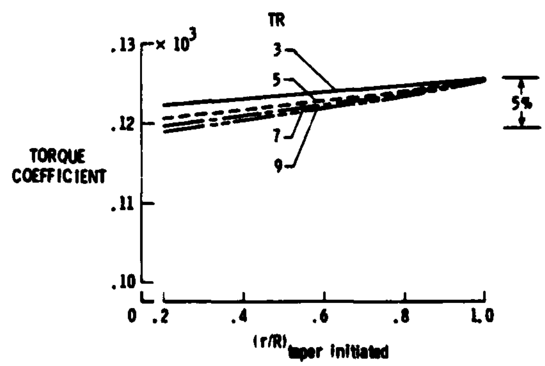


Figure 5.-Influence of location of initiation of taper and taper ratio on torque coefficient σ_T = 0.0464, θ = -10.6°, 8050 lbs, 4000'/95°, 110 knots.

blade chord (for a given taper initiation location and a given taper ratio) results in an increase in torque coefficient (compare figs. 4 and 5). The maximum torque advantage of planform change observed with constant area solidity (16 percent) is reduced to only 5 percent with constant thrust weighted solidity. Therefore, it is appropriate to consider the solidity requirements. It is well known that the solidity should be sufficient to (1) satisfy the hover design lift requirement, (2) avoid retreating blade stall at the forward flight design condition, and (3) avoid stall in maneuvers. Considering that the airfoil section lift coefficients required in hover are significantly less than those required in forward flight, the steady forward flight and maneuvering lift coefficient requirements become the controlling factors in the design.

Prior to considering the lift coefficient requirements and thus the airfoil requirement, it is desirable to consider the influence of changes in linear twist in forward flight. The twist influence at a taper ratio of 3 is indicated in figure 6 for constant area solidity. Unlike the results for hover (figure 3) the increase in twist for the rectangular blade (r/R = 1.0) had little influence on the configuration considered. The greatest influence of twist occurred with taper initiation near 0.5R; the reasons for these results are not readily apparent.

Airfoil Requirements

The hover and forward flight analysis discussed previously have shown, by example, the potential benefits of changes in blade planform and twist.

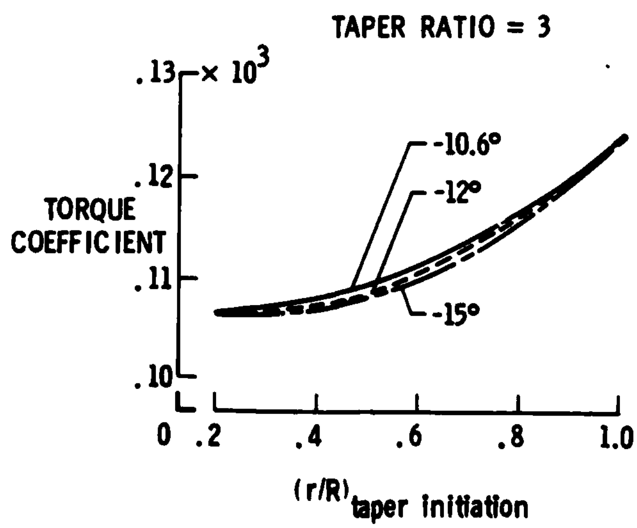


Figure 6.-Influence of linear twist on torque coefficient, σ = .0464, 8050 lbs, 4000'/95°, 110 knots.

The benefits observed at a constant area solidity were decreased when a constant thrust weighted solidity was maintained. Therefore, it is appropriate to now consider the airfoil requirements in light of the blade configurations previously discussed. This can be accomplished by applying the forward flight analytical program used in the earlier discussion; the forward flight analysis defines the upper and lower limits of lift coefficient requirements. As previously noted, the influences of airfoil stall and drag divergence can be avoided by applying the "ideal" airfoil so the first order lift coefficient-Mach number requirements for different configurations can be identified. Therefore, the airfoil lift requirements can be defined. The lift coefficient requirements will be unchanged for actual airfoil configurations if the rotor blade sections are operated in the linear range at all Mach numbers; only the drag coefficients will be different with different airfoils. For maneuvering flight the analysis becomes more complex and is not considered in this paper. In reviewing the airfoil requirements, the same 8050 pounds gross weight aircraft at 4000'/95° is considered.

The influence of position of initiation of taper on lift coefficient requirements is shown in figure 7. Section lift coefficients are presented

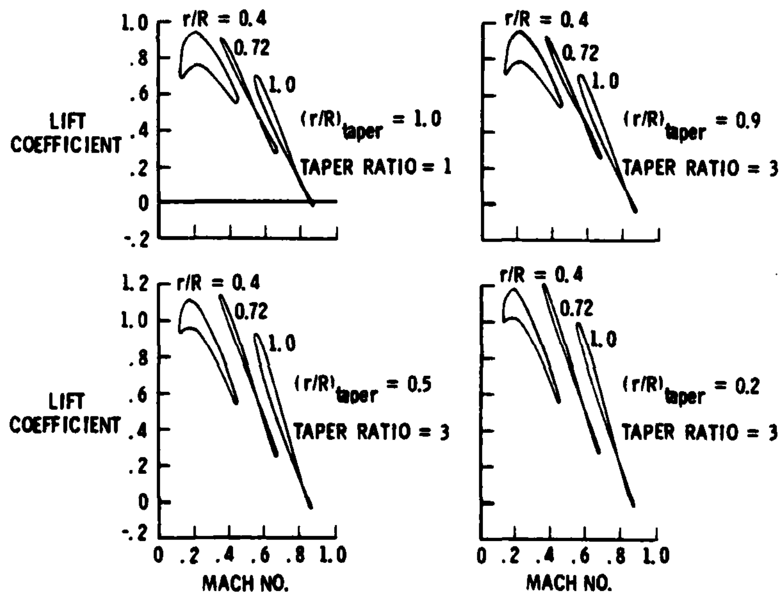


Figure 7.-Influence of position of initiation of taper on lift coefficient, σ = 0.0464, θ = -10.6°, 8050 lbs, 4000'/95°, 110 knots.

for three radial stations (0.4R, 0.72R, and 1.0R) as a function of section Mach number. Plots are provided for a rectangular rotor and for rotors with a taper ratio of 3 and with taper initiated at 0.9R, 0.5R, and 0.2R; area solidity is constant.

The inboard movement in radius at which taper is initiated results in a general increase in lift coefficient required at all radial stations. The primary increase is on the retreating side because the dynamic pressure is lower than on the advancing side. Changing from the rectangular blade to the blade tapered from 0.2R results in an increase in the lift coefficient required by as much as 0.3.

The influence of increasing the taper ratio from 3 to 5 or 9 are shown on figure 8; again, the area solidity is constant. With taper initiated at 0.9R, the lift coefficients are only slightly different from those for the rectangular configuration. However, with taper initiated at 0.5R and 0.2R,

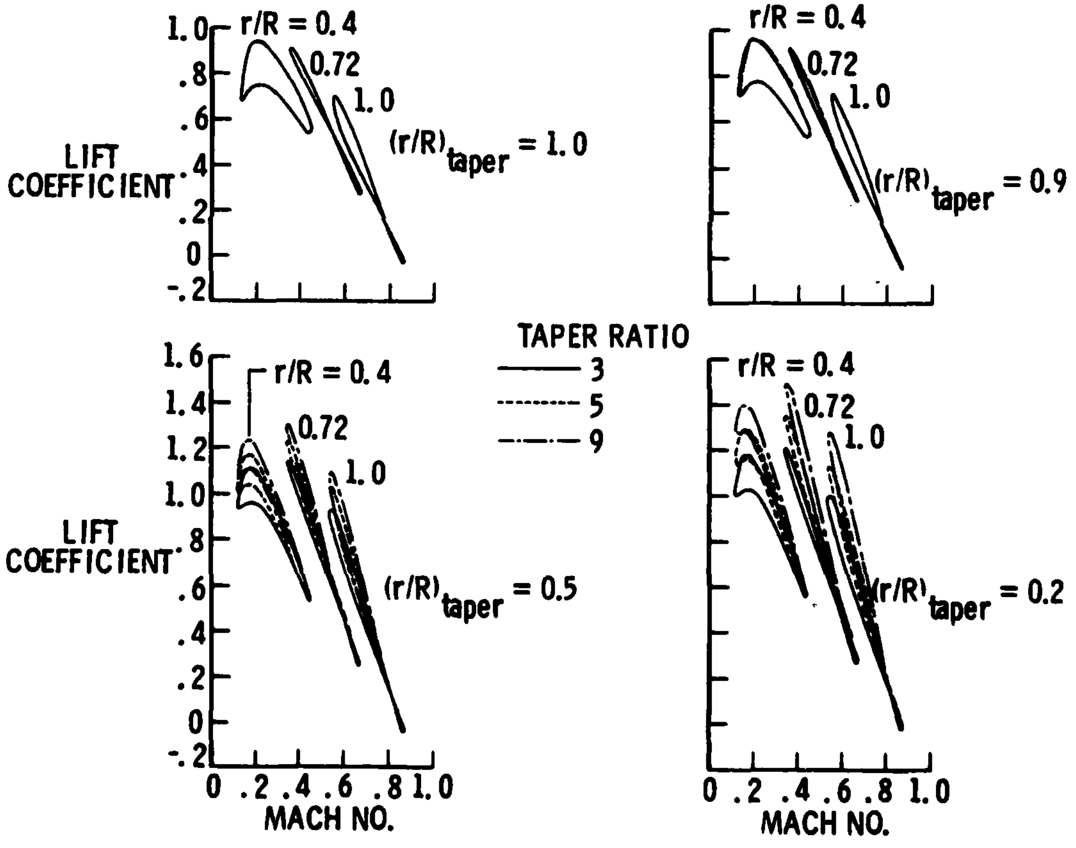


Figure 8.-Influence of taper ratio on lift coefficient, σ = 0.0464, θ = -10.6°, 8050 lbs, 4000'/95°, 110 knots.

the increases in required lift coefficient are as large as those resulting from the changes in taper initiation observed in figure 7. It is of interest to note here, at 1.0R, satisfying both a drag divergent Mach number of 0.87 and a maximum lift coefficient near 1.3 for taper initiation at 0.2R is beyond the capability of known airfoil sections; also, it should be noted that the position at which taper can be initiated and the blade taper ratio can be controlled by the maximum lift coefficients of the available airfoils.

As shown in figure 9, a reduction in the maximum lift requirement at the blade tip (r/R = 1.0) can be accomplished by increasing the linear twist of the blade. In the example shown, the increase is from -10.6 degrees to -15 degrees. The tip section lift coefficients are decreased at all Mach numbers. At 0.72R the twist has little influence on the operational lift coefficient. At 0.4R, the increased twist increases the inboard lift coefficients to result in an increase in inboard loading. The increase in twist results in requirements more consistent with current airfoil capability than those observed in figure 8 and permits adjustments in requirements to match the maximum lift coefficients of available airfoils.

The influences of blade solidity on the lift coefficient are shown in

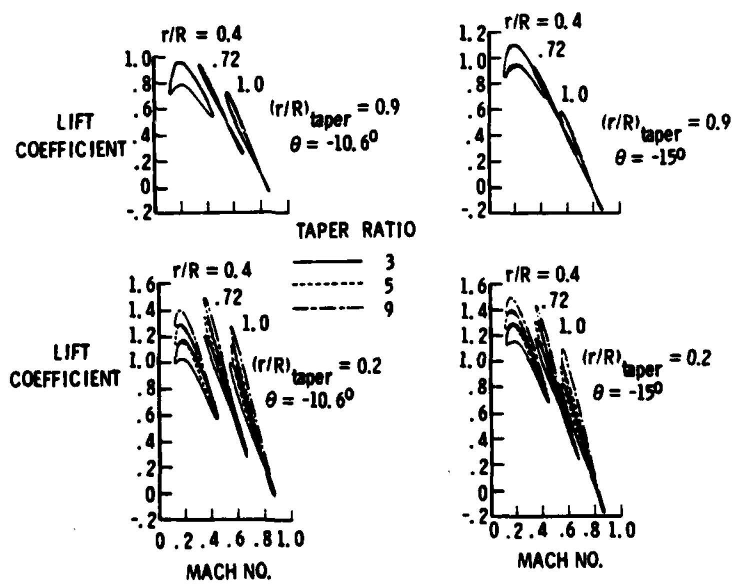


Figure 9.-Influence of taper ratio and linear twist on lift coefficient, σ = 0.0464, θ = -10.6°, 8050 lbs, 4000'/95°, 110 knots.

figure 10 where curves are presented at constant area and thrust weighted solidity. The plot at the upper left is once again for a rectangular blade and the other three are for a taper ratio of 3 with taper initiation locations at 0.9R, 0.5R, and 0.2R. The solidity increase results in reductions in lift coefficient. The greatest difference is indicated for the case with the most inboard taper initiation. It should be recalled, however, that the increase in solidity resulted in a reduction in the benefits of inboard taper initiation and taper ratio. The point to be recognized now is that the ability to obtain the improvements in the hover figure of merit (figs. 1 and 2) and the forward flight torque reductions (figs. 4 and 5). discussed earlier will depend on relationships between the lift coefficient-Mach number requirements and the lift coefficient-Mach number capability of the selected airfoil(s). The full advantages (for hover and forward flight) of the more inboard taper and the greater taper ratios can be realized only if the airfoils will satisfy the higher lift coefficient requirements at all radial stations and if drag divergence Mach number at all lift coefficients is not exceeded. As the characteristics of the airfoil are reviewed relative to the requirements, the selection of the initiation of taper, taper ratio, twist and solidity can be accomplished for approximating the best possible design. Also, the final solidity selection process should include consideration of maneuvering performance.

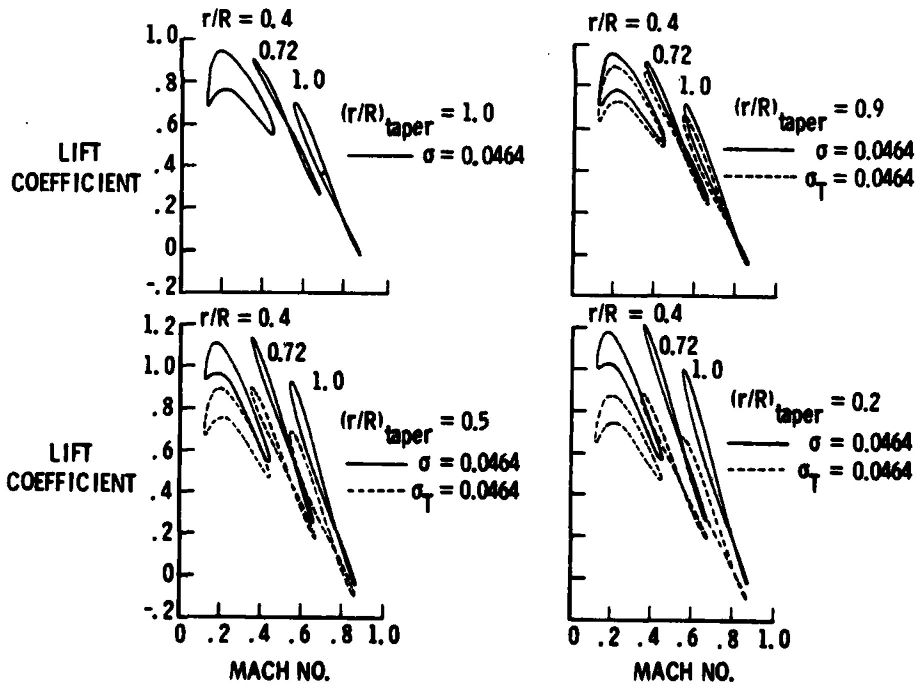


Figure 10.-Influence of solidity on lift coefficient, taper ratio = 3.0, θ = -10.6°, 8050 lbs, 4000'/95°, 110 knots.

Design Application

As previously noted, the design philosophy described herein has been applied to a UH-1 type rotor. For this design the goal was to provide an 8 percent reduction in hover power required when operating with 8050 pounds gross weight at 4000 feet altitude and 95 degrees Fahrenheit; the blade radius of 24 feet was to be maintained and forward flight performance was not to be degraded. The resulting configuration is shown on figure 11 along with the standard rectangular blade. The new configuration has a linear twist of -14 degrees, is rectangular to 50 percent radius, and then is tapered to the blade tip with a taper ratio of three. The area solidity is approximately 5 percent greater than that of the standard blade and the thrust and torque weighted solidity are reduced approximately 18 and 25 percent, respectively. Three airfoils (ref. 12) are distributed along the radius with a 12 percent thick section to 0.8R, a 10 percent thick section is located in the thickness transition region between 0.8R and 0.9R and an 8 percent thick section is applied from 0.9R to the blade tip.

The airfoils, planform, and twist selection began by considering the requirements suggested by figure 12 which displays the lift coefficient-Mach number requirements at the gross weight, altitude, and temperature addressed in the design. The forward flight velocity (110 knots) is near the maximum for these conditions in level flight. The maximum lift coefficient and the drag divergence Mach number of the NACA 0012 airfoil have been added to figure 12 for comparison. This figure suggests that sufficient lift coefficient is available so that the inboard regions might be more heavily loaded and that the drag divergence Mach number for the advancing region needs to be increased.

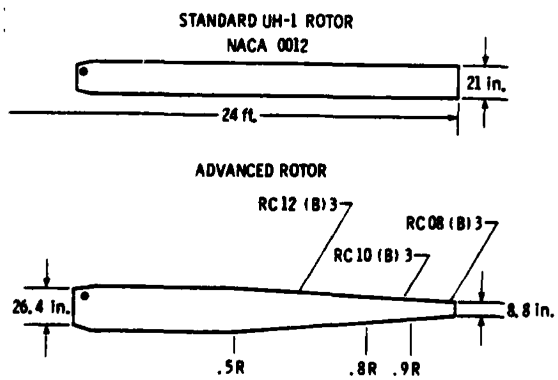


Figure 11.-Planform of standard and advanced rotor.

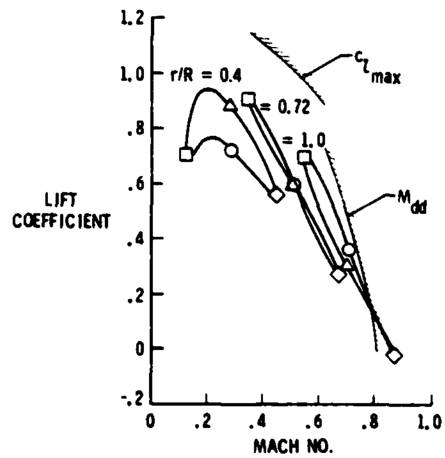
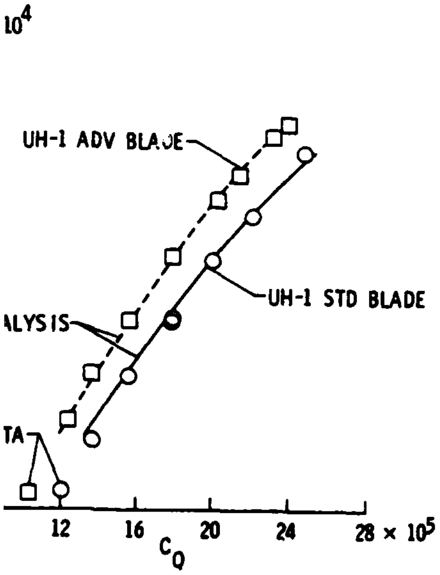


Figure 12.-Operational lift coefficients for UH-1D rotor, 8050 lbs, 4000'/95°, 110 knots.

baseline and advanced rotor configurations have been evaluated ASA Langley V/STOL tunnel on a UH-1 quarter-scale model complete elage (refs. 6 and 7). Data from the tests are presented in 3 to indicate the correlation between the hover analysis program (applied in the earlier discussion of this paper) and the hover m the V/STOL wind tunnel. In the analysis, two-dimensional air-a obtained in the Langley 6- x 28-inch transonic wind tunnel was Data for the NACA 0012 airfoil was applied in the standard blade and the airfoils noted on figure 11 were applied as distributed e blade radius. The design thrust coefficient corresponding to s weight and altitude/temperature is 0.0032. The experiment is in t with the analysis and provides validation of the design philoso-ented in this paper. At the design thrust coefficient, the rotor operated at a torque coefficient about 10 percent below the standard blade.

forward flight, the percentage improvement was greater than in igure 14). Although not shown on this figure, the experimental are consistent with analysis. The power reduction due to the blade is about 19 percent at the gross weight of this design. responds to a range increase of about 11 percent.



13.-Comparison of hover wind data and hover analysis.

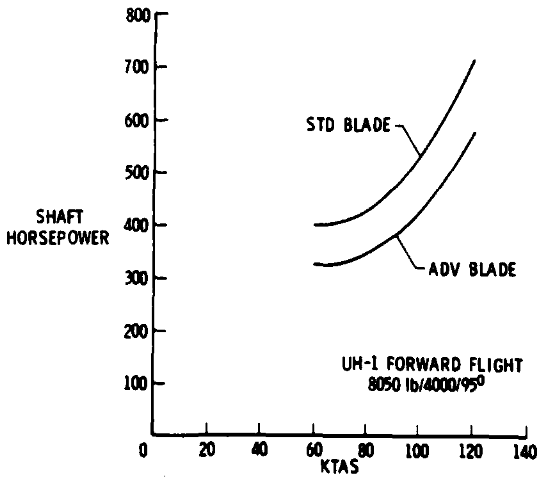


Figure 14.-Comparison of predicted forward flight performance of standard and an advanced UH-1 main rotor blade.

Concluding Remarks

It has been determined that the use of non-rectangular rotor blades can significantly improve the rotor performance, even if it is necessary to maintain a constant thrust weighted solidity. The preliminary design can be accomplished by applying "ideal" airfoil characteristics in simple hover and forward flight analyses. The "ideal" airfoil can also approximately define the airfoil lift coefficient requirements to lead to the final airfoil selection. The final design must then be evaluated with the characteristics of the airfoils to be applied. With the airfoil characteristics applied, adjustments may prove necessary in blade twist, planform and solidity.

Although not discussed in this paper, other performance requirements must be considered in the final design. Included would be autorotation characteristics which would depend in part on the mass distribution of the blade. Maneuver performance would also be addressed which would certainly depend on thrust weighted solidity. It is clear, however, that the development of improved airfoils to meet design requirements provides new opportunities in blade design.

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